

Astrophysical Models of r -Process Nucleosynthesis: An Update

Yong-Zhong Qian

School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

Abstract. An update on astrophysical models for nucleosynthesis via rapid neutron capture, the r process, is given. A neutrino-induced r process in supernova helium shells may have operated up to metallicities of $\sim 10^{-3}$ times the solar value. Another r -process source, possibly neutron star mergers, is required for higher metallicities.

Keywords: r process, neutrino interaction, supernovae, neutron star, black hole

PACS: 26.30.Hj, 26.30.Jk, 98.35.Bd, 97.60.Bw

INTRODUCTION

Two major mechanisms are responsible for making heavy elements beyond Fe: the slow (s) and rapid (r) neutron capture processes [1, 2]. This contribution focuses on recent developments in studies of the r process. Extensive reviews on the subject can be found in e.g., [3, 4, 5]. See [6] for a recent comprehensive review of s -process studies.

There are three major areas of r -process studies: (1) properties of extremely neutron-rich nuclei far from stability that are involved in the process, (2) astrophysical sites and associated conditions that can be used to assess the feasibility of an r process, and (3) frequencies of occurrences and other characteristics of potential r -process sources that are relevant for chemical evolution of galaxies. The second area is discussed in some detail below while the other two areas are mentioned only briefly.

The basic nuclear reactions involved in the r process are neutron capture, photo-disintegration, and β decay. The crucial nuclear input for the r process includes: (1) neutron capture rate coefficients $\langle \nu \sigma_{n,\gamma}(Z, A) \rangle$, which are averaged over thermal distributions of neutron and nuclei, (2) photo-disintegration rates $\Lambda_{\gamma,n}(Z, A)$, which can be obtained from $\langle \nu \sigma_{n,\gamma}(Z, A - 1) \rangle$ using detailed balance along with the neutron separation energy $S_n(Z, A)$ and relevant nuclear partition functions (e.g., [3]), and (3) β -decay rates $\lambda_\beta(Z, A)$. Here (Z, A) stands for a nucleus with proton number Z and mass number A . As the nuclei involved are extremely neutron rich, branching ratios for emission of up to several neutrons following a β decay also play an important role, especially during decay back to stability subsequent to freeze-out of rapid neutron capture. If the r process occurs in core-collapse supernovae, neutrino-induced reactions are important as charged-current (CC) ν_e capture is equivalent to β decay and neutrino-induced neutron emission is efficient following both CC and neutral-current (NC) excitation [7]. If the r process produces fissile nuclei, then rates for various fission channels (e.g., spontaneous, neutron-induced, β -delayed, neutrino-induced) and the corresponding mass distributions of fission fragments should also be included. Only a small fraction of the

nuclei involved in the r process are accessible to experiments, so the majority of the above nuclear input must be calculated from theory. As this input covers a wide range of nuclear processes, a self-consistent theoretical framework for all the input is essential. Fortunately, the next generation of rare isotope beam facilities such as FRIB, RIKEN, and FAIR will provide crucial guidance to the theoretical efforts in addition to direct measurements of masses and β -decay rates of some key nuclei for the r process.

By definition, an r process occurs when the neutron capture rate of a typical nucleus involved in the process exceeds its β -decay rate:

$$n_n \langle \nu \sigma_{n,\gamma}(Z, A) \rangle > \lambda_\beta(Z, A), \quad (1)$$

where n_n is the neutron (number) density at the astrophysical site. The quantity $\langle \nu \sigma_{n,\gamma}(Z, A) \rangle$ depends on the temperature T at the site while $\lambda_\beta(Z, A)$ is essentially independent of T . The above equation can be used to give a crude estimate of n_n required for an r process:

$$n_n > 10^{18} \left[\frac{10^{-17} \text{ cm}^3 \text{ s}^{-1}}{\langle \nu \sigma_{n,\gamma}(Z, A) \rangle} \right] \left[\frac{\lambda_\beta(Z, A)}{10 \text{ s}^{-1}} \right] \text{ cm}^{-3}, \quad (2)$$

where nominal values for $\langle \nu \sigma_{n,\gamma}(Z, A) \rangle$ and $\lambda_\beta(Z, A)$ have been used.

As a parcel of material undergoes r -processing, its n_n and T evolve with time t . The temperature T is crucial in determining the path of the r process. If T is always far below 10^9 K, the r process is cold and photo-disintegration is negligible. In this case, the r -process flow is controlled by the competition between neutron capture and β decay, and the path is populated dominantly by nuclei with $\lambda_\beta(Z, A) \sim n_n \langle \nu \sigma_{n,\gamma}(Z, A) \rangle$.

If T significantly exceeds 10^9 K initially, a hot r process occurs. For $T \sim 2 \times 10^9$ K and $n_n \gtrsim 10^{20} \text{ cm}^{-3}$, photo-disintegration is sufficiently fast to establish an equilibrium with neutron capture. In this $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium, the total abundance of nuclei with a specific Z is concentrated in a few so-called waiting-point nuclei, which are favored by the relevant n_n and T based mainly on their neutron separation energies $S_n(Z, A)$ and to a lesser extent, on their nuclear partition functions. As with any statistical equilibrium, the exact rates do not matter so long as they are fast enough for the equilibrium to hold. So the r -process path formed by the waiting-point nuclei is specified by n_n , T , and $S_n(Z, A)$ but is insensitive to $\langle \nu \sigma_{n,\gamma}(Z, A) \rangle$ and $\Lambda_{\gamma,n}(Z, A)$ when $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium holds. The β decay of the waiting-point nuclei regulates the relative abundances for different Z and dominantly controls the progress of the r -process flow. However, when n_n and T drop below some critical values, $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium breaks down. This allows $\langle \nu \sigma_{n,\gamma}(Z, A) \rangle$ and $\Lambda_{\gamma,n}(Z, A)$ to play important roles in determining the final abundance pattern produced by a hot r process.

For both cold and hot r processes, the overall abundance pattern produced in an individual astrophysical event, e.g., a core-collapse supernova, is a superposition of abundance patterns produced in different parcels of material that have undergone different time evolution of n_n and T . Astrophysical models of a hot r process are reviewed in the next section, followed by discussion of a cold r process induced by neutrino interaction in supernova helium shells.

ASTROPHYSICAL MODELS OF A HOT r PROCESS

In the absence of fission, the abundance pattern produced in a parcel of material undergoing a hot r process can be approximately characterized by the corresponding average mass number $\langle A_r \rangle$. By mass conservation,

$$\langle A_r \rangle = \langle A_s \rangle + n/s, \quad (3)$$

where $\langle A_s \rangle$ is the average mass number of seed nuclei that capture neutrons and n/s is the number ratio of neutrons to seed nuclei at the beginning of the r process. So the conditions required for a hot r process to produce nuclei with an average mass number $\langle A_r \rangle$ can be mapped to those giving rise to the corresponding $\langle A_s \rangle$ and n/s . The viability of a model for a hot r process can then be assessed by how seed nuclei are produced and how the neutron-to-seed ratio n/s is determined before the actual r process occurs.

A generic sequence of evolution prior to a hot r process can be illustrated by considering a parcel of material with an entropy $S \gtrsim 10$ in units of Boltzmann constant per baryon that adiabatically expands from $T \gtrsim 10^{10}$ K. The material at $T \gtrsim 10^{10}$ K is essentially composed of free nucleons with $Y_n \approx 1 - Y_e$, where Y_n is the number fraction of neutrons and Y_e is the electron fraction (net number of electrons per nucleon). Given S and Y_e , the nucleosynthesis during the expansion can be calculated once the time evolution of T is specified. A convenient parametric form is $T(t) = T(0) \exp(-t/\tau_{\text{dyn}})$, where τ_{dyn} is a constant dynamic timescale.

For $Y_e < 0.5$, nearly all protons are assembled into ${}^4\text{He}$ when T decreases to $\sim 5 \times 10^9$ K. At lower T , an α process occurs to burn neutrons and ${}^4\text{He}$ [8]. Here the role of S is manifest. Due to the absence of stable or long-lived nuclei at $A = 5$ and 8, the nuclear flow must go through the three-body reaction ${}^4\text{He} + {}^4\text{He} + n \rightarrow {}^9\text{Be} + \gamma$ to produce nuclei beyond ${}^4\text{He}$. For $S > 100$, there are a sufficient number of photons at or above 1.573 MeV, the threshold to break up ${}^9\text{Be}$, in the Planck distribution for $5 \times 10^9 \gtrsim T \gtrsim 3 \times 10^9$ K. So the higher S is, the more inefficiently heavy nuclei are produced. In any case, charged-particle reactions effectively cease when T drops to $\sim 3 \times 10^9$ K due to the Coulomb barrier. By then the inventory of heavy nuclei produced typically have $A \sim 60\text{--}90$. These nuclei act as seed nuclei to capture the remaining neutrons during the subsequent r process as T continues to decrease.

Clearly, there are an infinite number of combinations of S , Y_e , and τ_{dyn} that can give the same $\langle A_r \rangle$ according to Eq. (3). This can be seen from the determination of n/s . Approximately speaking, there are three different ways to produce a higher n/s : (1) a lower Y_e to increase the initial neutron abundance, (2) a higher S to suppress production of seed nuclei by keeping the abundance of ${}^9\text{Be}$ low, and (3) a smaller τ_{dyn} also to reduce seed production but by shortening the duration of the α process. The r -process abundance pattern in the solar system is characterized by two peaks at $A \sim 130$ and 195, respectively. To produce the peak at $A \sim 195$ requires $\langle A_r \rangle \approx 200$. Figure 1 shows three contours in the (S, Y_e) -plane that would all give $\langle A_r \rangle \approx 200$ for the corresponding values of τ_{dyn} indicated. These results are taken from [9] and can be used to gauge the viability of an astrophysical environment to produce an r -process abundance peak at $A \sim 195$. Similar results can be found in [10, 11]. Specific astrophysical models of a hot r process are discussed below.

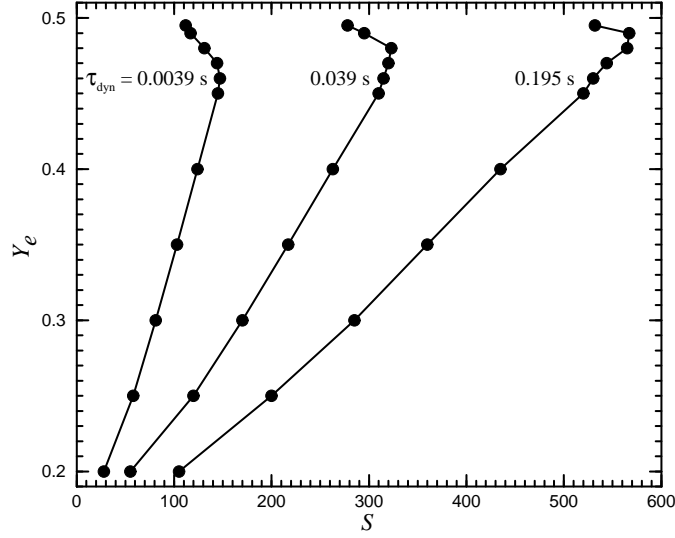


FIGURE 1. Combinations of S , Y_e , and τ_{dyn} required for adiabatically expanding material to produce nuclei with $\langle A_r \rangle \approx 200$ through a hot r process. See text and [9] for details.

Neutrino-driven winds from proto-neutron stars

Core-collapse supernovae are intimately associated with neutrinos. Essentially all the gravitational binding energy of a proto-neutron star formed in these events, $\sim 3 \times 10^{53}$ erg, is radiated in ν_e , $\bar{\nu}_e$, ν_μ , $\bar{\nu}_\mu$, ν_τ , and $\bar{\nu}_\tau$ over ~ 10 s. A fraction of the ν_e and $\bar{\nu}_e$ can be absorbed by the material immediately above the proto-neutron star through the reactions

$$\nu_e + n \rightarrow p + e^-, \quad (4)$$

$$\bar{\nu}_e + p \rightarrow n + e^+. \quad (5)$$

During the ~ 10 s of neutrino emission, the proto-neutron star blows a wind as the energy deposited by the above reactions continuously lifts shells of material out of its gravitational potential well. If reaction (5) proceeds more efficiently than reaction (4), the wind material is driven neutron rich ($Y_e < 0.5$) [12]. When this material reaches sufficiently large radii, these reactions effectively cease due to small neutrino fluxes. Subsequently, the material approximately undergoes the generic evolution outlined above for adiabatic expansion with fixed S , Y_e , and τ_{dyn} .

Earlier studies of nucleosynthesis in neutrino-driven winds based on the supernova models of J. R. Wilson showed that a hot r process occurs (e.g., [13, 14]). However, later studies [15, 16, 17, 18, 19, 20] could not reproduce the high entropies in these models. Typically, $10 \lesssim S \lesssim 100$, $0.4 \lesssim Y_e \lesssim 0.5$, and $0.01 \lesssim \tau_{\text{dyn}} \lesssim 0.1$ s were obtained. For these conditions, the elements Sr, Y, and Zr with $A \sim 90$ are readily produced, and for the most favorable among these conditions, the elements from Pd and Ag with $A \sim 110$ up to Te immediately below $A \sim 130$ can be produced (e.g., [9]). However, all these elements are produced in quasi-equilibrium of forward and reverse reactions involving photon, neutron, proton, and α particle but not by an r process (e.g., [8]). In fact, heavy

r -process elements with $A > 130$, especially those in the solar r -process abundance peak at $A \sim 195$, cannot be produced under these conditions (see Fig. 1).

As Y_e depends on the competition between reactions (4) and (5), it is extremely sensitive to the difference between the emission characteristics of ν_e and $\bar{\nu}_e$ [12]. In contrast, S and τ_{dyn} are not sensitive to this difference as they depend on the net heating by both ν_e and $\bar{\nu}_e$. Recent calculations including more neutrino transport processes showed that neutrino-driven winds are always proton rich ($Y_e > 0.5$) [19, 21]. This gives rise to a new process of nucleosynthesis, the νp process [22, 23], which produces elements beyond the Fe group mostly via proton capture. Without neutrinos, those “waiting-point” nuclei in $(p, \gamma) \rightleftharpoons (\gamma, p)$ equilibrium must β decay before the nuclear flow can proceed further (cf. a hot r process) and a waiting-point nucleus with a very slow β -decay rate effectively terminates the flow. The flow proceeds much further in the presence of an intense $\bar{\nu}_e$ flux because the neutron produced by reaction (5) can enable an (n, p) reaction that has the same effect as but is much faster than β decay. Therefore, the νp process can produce elements far beyond the Fe group. It was shown that the elements from Sr, Y, and Zr to Pd and Ag with $A \sim 90$ –110 can be produced in both proton-rich and neutron-rich winds [24]. So while neutrino-driven winds are unlikely to produce heavy r -process elements with $A > 130$, they are an important source of the above elements. Further, they served as a detailed case study of novel processes of nucleosynthesis that were not envisioned in the classical papers of Burbidge et al. [1] and Cameron [2] on the origin of the elements.

Shocked surface layers of O-Ne-Mg cores

Stars with masses $M \gtrsim 11M_\odot$ develop Fe cores and those with $8 \lesssim M < 11M_\odot$ develop O-Ne-Mg cores before they undergo core collapse (e.g., [25]). These two groups of stars differ greatly in structure as the density above an O-Ne-Mg core falls off much more drastically than that above an Fe core [26]. So far O-Ne-Mg core-collapse supernovae are the only case for which neutrino heating [mostly via reactions (4) and (5) as in the case of neutrino-driven winds] has been demonstrated to result in a successful explosion (e.g. [27]).

The surface layers of an O-Ne-Mg core are slightly neutron rich due to processing by pre-supernova nuclear burning. The evolution of such a layer subsequent to being struck by the supernova shock again approximately follows adiabatic expansion with fixed S , Y_e , and τ_{dyn} . Due to the steep density gradient above the O-Ne-Mg core, the shocked material may expand rapidly with $\tau_{\text{dyn}} \sim 10^{-3}$ s. This along with $S \sim 100$ and $Y_e < 0.5$ (see Fig. 1) would enable a hot r process to produce nuclei with $\langle A_r \rangle \approx 200$ [28]. However, current models of O-Ne-Mg core collapse based on Nomoto’s models of the associated supernova progenitors [26] only give a weak explosion, for which the shocked surface layers of the core expand with $\tau_{\text{dyn}} \gg 10^{-3}$ s and $S \ll 100$ [29]. As these layers are not extremely neutron rich, no hot r process can occur under the conditions obtained in current models. It remains to be seen if more favorable conditions can be obtained for new models of stars that develop O-Ne-Mg cores.

Winds from accretion disks of black holes

Figure 1 shows that for $\tau_{\text{dyn}}/S^3 \sim 2 \times 10^{-7}$ s with $25 \lesssim S \lesssim 100$ and $3.9 \times 10^{-3} \lesssim \tau_{\text{dyn}} \lesssim 0.195$ s, nuclei with $\langle A_r \rangle \approx 200$ can be produced by a hot r process for $Y_e \sim 0.2$. The above ranges of S and τ_{dyn} occur in neutrino-driven winds from proto-neutron stars. However, $Y_e \sim 0.2$ cannot be obtained in these winds without invoking new physics such as sterile neutrinos [30]. Therefore, it is important to explore alternative candidate environments for a hot r process where such low Y_e values may be obtained more naturally along with similar S and τ_{dyn} to those in neutrino-driven winds.

Some Fe-core collapse supernovae are expected to produce black holes rather than neutron stars. An accretion disk typically forms around the black hole. Such disks can also form in mergers of two neutron stars or of a neutron star with a black hole. The disk material close to the black hole is hot and dense and emits neutrinos similarly to the surface layers of a proto-neutron star. In addition, this material may be very neutron rich as a result of the reaction $e^- + p \rightarrow n + \nu_e$. A fraction of this material is ejected in winds due to heating by dynamic processes in the disk or by neutrino reactions (4) and (5). Parametric models suggest that adequate conditions, in particular low Y_e values, may be obtained in these winds for a hot r process to occur [31, 32, 33, 34]. It remains to be seen if such conditions can be derived in self-consistent models of the accretion disk and the associated winds. It is especially important that detailed neutrino transport in the disk be carried out similarly to that in modern core-collapse supernova models.

Neutron star mergers

Material of low Y_e stocked up inside a neutron star can be released by tidal force during mergers of two neutron stars or of a neutron star with a black hole. Once released from the strong gravitational hold of its parent neutron star, such material undergoes decompression, which is accompanied by heating due to β decay. The possibility of a hot r process during the expansion of decompressed neutron-star matter was discussed in the pioneering work of Lattimer et al. [35] and more recently in [36, 37]. An interesting feature of this r -process model is that the nuclear flow typically reaches fissile nuclei and becomes cyclic as the fission fragments capture neutrons to replenish the flow. This fission cycling is expected to produce a robust abundance pattern at $A > 130$, which appears to be in accord with observations of metal-poor stars in the Galactic halo but with some notable exceptions (e.g., [38, 39]).

A potential problem with r -process models based on neutron star mergers is that these events occur $\sim 10^3$ times less frequently than core-collapse supernovae in the Galaxy. Were neutron star mergers a major source for heavy r -process elements with $A > 130$, stars with the earliest such enrichments would have been enriched with high Fe abundances by the numerous core-collapse supernovae that had already occurred prior to the contributing r -process event [40, 41]. This is in contradiction to observations of a number of metal-poor stars that are enriched in heavy r -process elements but have $[\text{Fe}/\text{H}] \equiv \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_{\odot} \lesssim -3$ (e.g., [38]). It remains to be seen if more detailed models of Galactic chemical evolution may resolve the above difficulty.

NEUTRINO-INDUCED NUCLEOSYNTHESIS IN SUPERNOVA HELIUM SHELLS: A COLD r PROCESS

The notion of a unique type of sources that produce heavy r -process elements with $A > 130$ over the entire history of the Galaxy has some appeal but is far from required by observations (e.g., [39, 42]). As discussed above, winds from black hole accretion disks and decompressed ejecta from neutron star mergers could both be production sites for such elements. The difficulty of neutron star mergers to account for observed enrichments of heavy r -process elements at $[\text{Fe}/\text{H}] \lesssim -3$ leads to the question whether other sources could have operated at such low metallicities. In fact, such a source was proposed by Epstein, Colgate, and Haxton (ECH) [43]. In their model, NC neutrino reactions on ${}^4\text{He}$ nuclei produce neutrons for an r process via ${}^4\text{He}(\nu, \nu n){}^3\text{He}(n, p){}^3\text{H}$ or ${}^4\text{He}(\nu, \nu p){}^3\text{H}$ followed by ${}^3\text{H}({}^3\text{H}, 2n){}^4\text{He}$. This occurs in helium shells of metal-poor core-collapse supernovae, where neutrons are left alone by the predominant ${}^4\text{He}$ nuclei but captured by the Fe nuclei acquired at the birth of the supernova progenitors. The helium shells have $T \sim 10^8$ K, and therefore, the ECH mechanism is a cold r process. The neutron density for this mechanism depends on the competition between production by neutrino reactions and capture by Fe and other nuclei. Consequently, $n_n \gtrsim 10^{18} \text{ cm}^{-3}$ required for an r process [see Eq. (2)] can only be obtained at low metallicities. The ECH mechanism was critiqued in [44] as viable only for low-mass metal-poor supernovae, where helium shells are located at relatively small radii to ensure sufficiently large neutrino fluxes. Follow-up studies were carried out in e.g., [45].

Recently, it was shown that a modified ECH mechanism could operate in core-collapse supernovae with $[\text{Fe}/\text{H}] \lesssim -3$ over a range of progenitor masses [46]. For a $15 M_\odot$ progenitor with $[\text{Fe}/\text{H}] \sim -4.5$ [25], a cold r process occurs in the outer helium shells at radii of $\sim 10^{10}$ cm, where the abundances of ${}^{12}\text{C}$ and ${}^{16}\text{O}$ nuclei produced by pre-supernova helium burning are too low to cause significant neutron capture. The CC reaction ${}^4\text{He}(\bar{\nu}_e, e^+ n){}^3\text{H}$ turns out to be the dominant source of neutrons because the temperature is too low for the reaction ${}^3\text{H}({}^3\text{H}, 2n){}^4\text{He}$ to be effective [46]. Further, the CC reaction rate is greatly enhanced when the energy spectra of $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ are much harder than that of $\bar{\nu}_e$ at emission and an inverted neutrino mass hierarchy enables $\bar{\nu}_e \rightleftharpoons \bar{\nu}_{\mu, \tau}$ transformation below the outer helium shells [46]. More systematic studies of the modified ECH mechanism are needed to assess its contribution to Galactic chemical evolution. It is conceivable that this mechanism operated in the early Galaxy until $[\text{Fe}/\text{H}] \sim -3$ and neutron star mergers provided the subsequent r -process enrichments.

ACKNOWLEDGMENTS

I thank Projjwal Banerjee, Wick Haxton, and Alexander Heger for collaboration on neutrino-induced nucleosynthesis in core-collapse supernovae, and Jie Meng and Bao-hua Sun for collaboration on nuclear physics input for the r process. This work is supported in part by the U.S. DOE under DE-FG02-87ER40328 and by the National Natural Science Foundation of China under Joint Research Grant No. 11128510.

REFERENCES

1. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, *Rev. Mod. Phys.* **29**, 547–650 (1957).
2. A. G. W. Cameron, *Publ. Astron. Soc. Pac.* **69**, 201–222 (1957).
3. J. J. Cowan, F.-K. Thielemann, and J. W. Truran, *Phys. Rep.* **208**, 267–394 (1991).
4. Y.-Z. Qian, *Prog. Part. Nucl. Phys.* **50**, 153–199 (2003).
5. M. Arnould, S. Goriely, and K. Takahashi, *Phys. Rep.* **450**, 97–213 (2007).
6. F. Käppeler, R. Gallino, S. Bisterzo, and W. Aoki, *Rev. Mod. Phys.* **83**, 157–194 (2011).
7. Y.-Z. Qian, W. C. Haxton, K. Langanke, and P. Vogel, *Phys. Rev. C* **55**, 1532–1544 (1997).
8. S. E. Woosley and R. D. Hoffman, *Astrophys. J.* **395**, 202–239 (1992).
9. R. D. Hoffman, S. E. Woosley, and Y.-Z. Qian, *Astrophys. J.* **482**, 951–962 (1997).
10. B. S. Meyer and J. S. Brown, *Astrophys. J. Suppl. Ser.* **112**, 199–220 (1997).
11. C. Freiburghaus et al., *Astrophys. J.* **516**, 381–398 (1999).
12. Y.-Z. Qian, G. M. Fuller, G. J. Mathews, R. W. Mayle, J. R. Wilson, and S. E. Woosley, *Phys. Rev. Lett.* **71**, 1965–1968 (1993).
13. B. S. Meyer, G. J. Mathews, W. M. Howard, S. E. Woosley, and R. D. Hoffman, *Astrophys. J.* **399**, 656–664 (1992).
14. S. E. Woosley, J. R. Wilson, G. J. Mathews, R. D. Hoffman, and B. S. Meyer, *Astrophys. J.* **433**, 229–246 (1994).
15. J. Witti, H.-T. Janka, and K. Takahashi, *Astron. Astrophys.* **286**, 841–856 (1994).
16. Y.-Z. Qian and S. E. Woosley, *Astrophys. J.* **471**, 331–351 (1996).
17. S. Wanajo, T. Kajino, G. J. Mathews, and K. Otsuki, *Astrophys. J.* **554**, 578–586 (2001).
18. T. A. Thompson, A. Burrows, and B. S. Meyer, *Astrophys. J.* **562**, 887–908 (2001).
19. T. Fischer, S. C. Whitehouse, A. Mezzacappa, F.-K. Thielemann, and M. Liebendörfer, *Astron. Astrophys.* **517**, A80 (2010).
20. L. F. Roberts, S. E. Woosley, and R. D. Hoffman, *Astrophys. J.* **722**, 954–967 (2010).
21. L. Hüdepohl, B. Müller, H.-T. Janka, A. Marek, and G. G. Raffelt, *Phys. Rev. Lett.* **104**, 251101 (2011).
22. J. Pruet, S. E. Woosley, R. Buras, H.-T. Janka, and R. D. Hoffman, *Astrophys. J.* **623**, 325–336 (2005).
23. C. Fröhlich et al., *Astrophys. J.* **637**, 415–426 (2006).
24. A. Arcones and F. Montes, *Astrophys. J.* **731**, 5 (2011).
25. S. E. Woosley, A. Heger, and T. A. Weaver, *Rev. Mod. Phys.* **74**, 1015–1071 (2002).
26. K. Nomoto, *Astrophys. J.* **277**, 791–805 (1984).
27. F. S. Kitaura, H.-T. Janka, and W. Hillebrandt, *Astron. Astrophys.* **450**, 345–350 (2006).
28. H. Ning, Y.-Z. Qian, and B. S. Meyer, *Astrophys. J.* **667**, L159–L162 (2007).
29. H.-T. Janka, B. Müller, F. S. Kitaura, and R. Buras, *Astron. Astrophys.* **485**, 199–208 (2008).
30. G. C. McLaughlin, J. M. Fetter, A. B. Balantekin, and G. M. Fuller, *Phys. Rev. C* **59**, 2873–2887 (1999).
31. J. Pruet, S. E. Woosley, and R. D. Hoffman, *Astrophys. J.* **586**, 1254–1261 (2003).
32. R. Surman, G. C. McLaughlin, and W. R. Hix, *Astrophys. J.* **643**, 1057–1064 (2006).
33. R. Surman, G. C. McLaughlin, M. Ruffert, H.-T. Janka, and W. R. Hix, *Astrophys. J.* **679**, L117–L120 (2008).
34. S. Wanajo and H.-T. Janka, arXiv:1106.6142.
35. J. M. Lattimer, F. Mackie, D. G. Ravenhall, and D. N. Schramm, *Astrophys. J.* **213**, 225–233 (1977).
36. C. Freiburghaus, S. Rosswog, and F.-K. Thielemann, *Astrophys. J.* **525**, L121–L124 (1999).
37. S. Goriely, A. Bauswein, and H.-T. Janka, *Astrophys. J.* **738**, L32 (2011).
38. C. Sneden, J. J. Cowan, and R. Gallino, *Annu. Rev. Astron. Astrophys.* **46**, 241–288 (2008).
39. S. Honda, W. Aoki, Y. Ishimaru, and S. Wanajo, *Astrophys. J.* **666**, 1189–1197 (2007).
40. Y.-Z. Qian, *Astrophys. J.* **534**, L67–L70 (2000).
41. D. Argast, M. Samland, F.-K. Thielemann, and Y.-Z. Qian, *Astron. Astrophys.* **416**, 997–1011 (2004).
42. G. J. Wasserburg, M. Busso, and R. Gallino, *Astrophys. J.* **466**, L109–L113 (1996).
43. R. I. Epstein, S. A. Colgate, and W. C. Haxton, *Phys. Rev. Lett.* **61**, 2038–2041 (1988).
44. S. E. Woosley, D. H. Hartmann, R. D. Hoffman, and W. C. Haxton, *Astrophys. J.* **356**, 272–301 (1990).
45. D. K. Nadyozhin and I. V. Panov, *J. Phys. G* **35**, 014061 (2008).
46. P. Banerjee, W. C. Haxton, and Y.-Z. Qian, *Phys. Rev. Lett.* **106**, 201104 (2011).